

THE MISSION AND OPERATION OF THE MARS PATHFINDER MICROROVER

J. Matijevic

Jet Propulsion Laboratory - California Institute of Technology
4600 Oak Grove Drive
Pasadena, California 91109
E-mail: Jacob_R_Matijevic@jpl.nasa.gov

D. Shirley

Jet Propulsion Laboratory - California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109
E-mail: Donna_L_Shirley@jpl.nasa.gov

Abstract: The Microrover Flight Experiment (MFEX) is a NASA OACT flight experiment which is planned to be delivered and integrated with the Mars Pathfinder (MPF) lander and spacecraft system for landing on Mars on July 4, 1997. After landing, the MFEX rover is deployed from the lander and begins a nominal 7 sol (1 sol = 1 Martian day) mission to conduct a series of technology experiments, deploy an alpha proton x-ray spectrometer (APXS) on rocks and soil, and image the lander. This mission is conducted under the constraints of a once-per-sol opportunity for command and telemetry transmissions between the lander and earth operators. As such, the MFEX rover must be capable of carrying out its mission in a form of supervised autonomous control, in which, for example, goal locations are commanded and the rover navigates and safely traverses to these locations. In this paper, the mission of the MFEX is described along with the on-board and ground based systems which provide the capability for operating the vehicle.

Keywords: autonomous mobile robot, navigation, mobility, hazard avoidance

1. INTRODUCTION

The Microrover Flight Experiment (MFEX) is a NASA OACT flight experiment which is integrated with the Mars Pathfinder (MPF) lander and is planned for launch in a 30-day window beginning on December 2, 1996 (Shirley, D. 1993). After landing on Mars July 4, 1997, the MFEX rover is deployed from the lander and begins a nominal 7 sol mission conducting a series of experiments which will validate technologies for an autonomous mobile vehicle. In addition, the MFEX rover will deploy its science instrument, an alpha proton x-ray spectrometer (APXS), on rocks and soil to determine the elemental composition.

Lastly, the rover will image the MPF lander as part of an engineering assessment after landing.

2. DESCRIPTION

The MFEX rover (see Fig.1) is a 6-wheeled vehicle, 10.5kg in mass (including payload), and 65cm long, 48cm wide and 30cm tall. The rover is of a rocker bogie design (Bickler, D.B. 1992) which allows the traverse of obstacles a wheel diameter (13cm) in size. Each wheel has cleats and is independently actuated and geared providing for climbing, in soft sand and scrambling over rocks. The front and rear wheels are independently steered, allowing the vehicle to turn in place. The vehicle has a top speed of 0.4m/min.

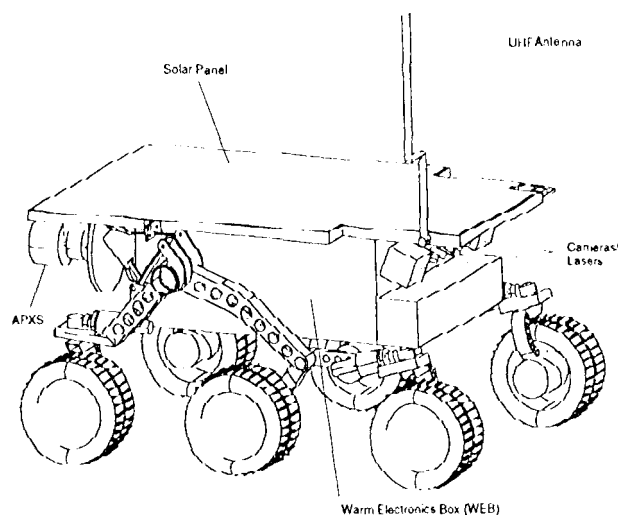


Fig. 1. Mars Pathfinder Microrover

The rover is powered by a 0.22sqm solar panel comprised of 13 strings of 18, 5.5mil GaAs cells each. The solar panel is backed up by 9 LiSOCl₂ 1-cell sized primary batteries, providing up to 150W-hr of energy. The combined panel and battery system allows the rover to draw up to 30W of peak power while the peak panel production is 16W. The normal driving power requirement is 10W.

Rover components not designed to survive ambient Mars temperatures (-110degC during a Martian night) are contained in the warm electronics box (WEB). The WEB is insulated with solid silica aerogel, coated with low emissivity paints, and heated under computer control during the day. This design allows the WEB to maintain components between -40degC and +40degC during a sol.

Control is provided by an integrated set of computing and power distribution electronics. The computer is an 80C85 rated at 100Kips which uses, in a page swapping fashion, 176Kbytes of PROM and 576 Kbytes of RAM. The computer performs I/O to some 70 sensor channels and services such devices as the cameras, modem, motors and experiment electronics.

Vehicle motion control is accomplished through the on/off switching of the drive or steering motors. An average of motor encoder (drive) or potentiometer (steering) readings determines when to switch off the motors. When motors are off, the computer conducts a proximity and hazard detection function, using its laser striping and carom system to determine the presence of obstacles in its path. The vehicle is steered autonomously to avoid obstacles but continues to achieve the commanded goal location. While stopped, the computer also updates its measurement of distance traveled and heading using the average of the

number of turns of the wheel motors and an on-board gyro. This provides an estimate of progress to the goal location.

Command and telemetry is provided by UHF radio modems on the rover and lander. During the day, the rover regularly requests transmission of any commands sent from earth and stored on the lander. When commands are not available, the rover transmits any telemetry collected during the last interval between communication sessions. The telemetry received by the lander is stored and forwarded to the earth. In addition, the communication system is used to provide a 'heartbeat' signal during vehicle driving. While stopped the rover sends a signal to the lander. Once acknowledged by the lander, the rover proceeds to the next stopping point along its traverse.

3. MISSION

The MFE-X mission consists of: (1) conducting a series of experiments which validate technologies for an autonomous mobile vehicle, (2) deploying the MFE-X science instrument, an alpha proton x-ray spectrometer (APXS), on rocks and soil, and (3) imaging, the MPF lander as part of an engineering assessment after landing. At this writing, the MFE-X mission plan is shown in Fig. 2.

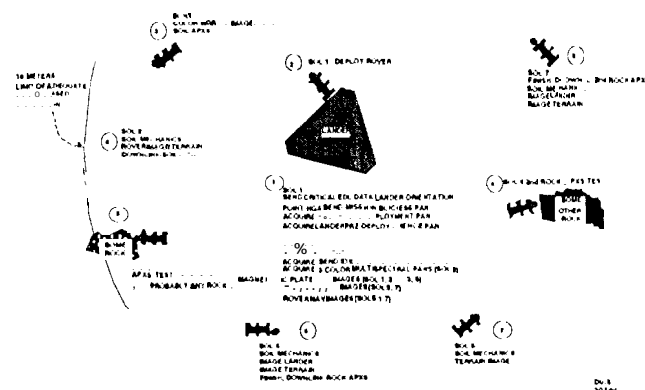


Fig. 2. Mars Pathfinder lander and rover: nominal 7 sol scenario

3.1 Technology Experiments

3.1.1 Mars Terrain Geometry Reconstruction from Imagery

Each sol images are taken by the rover and lander as a means of planning the next sol of operations. As a collection these images will be used to construct a map of the landing site. The lander camera can be panned in azimuth a full 360deg and in elevation approximately 160deg, providing in a segmented form, a complete image of the landing site. Each image segment is a 256 pixel square and has a field of view of 14deg by 14deg. Each image will be provided in stereo and color at 1 nu-ad/pixel.

The images taken by the rover are a series of 'snap shots' provided at wide angle of 127deg by 95deg at 3mrad/pixel. Three such images (one from each of the two front, stereo capable cameras and cmc from the rear) are taken at each sol's end of rover traverse. In addition, selected images of patches of soil, rocks and related surface features are obtained in support of other portions of the rover mission.

Each of these rover images can be correlated to the location of the rover where the images were taken. The location of the rover is given by both the cm-board odometer estimate and the location of the vehicle as derived from images from the lander cameras.

3.1.2 Basic Soil Mechanics

In a soil sample, as a single front or rear wheel is turned in place, the motor current is measured and an estimate of torque is derived. This torque applied by an essentially incompressible wheel gives an estimate of applied force. Potentiometers at the bogies estimate wheel sinkage.

By repeating the experiment with different front and rear wheels, an estimate of the shear force of the soil, F , can be derived from:

$$\Delta F = (W_i - W_j) \tan \phi \quad (1)$$

where W is a wheel load and ϕ is the angle of internal friction as estimated from the wheel sinkage. A model of the soil (equation (4)) then can be derived from:

$$F = CA + W \tan \phi \quad (2)$$

$$tA = CA + pA \tan \phi \quad (3)$$

$$t = c + p \tan \phi \quad (4)$$

where A is the wheel contact area, c the soil cohesion, p the tire ground pressure, and t the shear strength of the soil.

Once the parameters representing the soil are developed, a fit to a simplified model of a vehicle in interaction with soil will provide estimates of rolling resistance, sinkage and traction (Bekker, M. G. 1969).

3.1.3 Dead Reckoning Sensor Performance and Path Reconstruction/Recovery

During traverses the rover updates its position using estimate of position (as derived from an average of wheel encoder values) and heading (as derived from the rate gyro). Once per sol, the lander will image the vehicle position, providing an opportunity for a correction of the estimate on a bird the rover through a commanded parameter update.

The telemetry logged by the rover during traverses include measurements of the vehicle odometer, orientation, articulation, and tilt (as provided by a set of 3 single axis accelerometers). In addition, at approximately each 10sec interval of traverse, the rover stops and exercises its hazard

avoidance system. A sparse map of obstacle distances and heights in front of the vehicle is developed and used by the vehicle to avoid a trafficability hazard (e.g., a hole, an anomalous vehicle tilt during traverse or a step). This sparse map is also part of the vehicle telemetry.

Once gathered and analyzed, the telemetry provides a means of reconstructing the path traversed by the vehicle. In addition, since the path actually traversed by the vehicle will vary from the commanded (or expected) path, this experiment provides data which can be used to evaluate the capabilities of the sensors and algorithms of the position estimation and hazard avoidance systems.

3.1.4 Sinkage in Each Martian Soil Type

At the end of selected wheel rotations performed during the soil mechanics experiment, images are taken. These images are of both the rut produced by the wheel rotations and the wheel sitting in the rut. In the former image an estimate of the angle of repose of the soil can be derived. In the latter, an estimate of the sinkage can be derived. Each provides another measurement of ϕ (see 3.1.2) developed (initially) from the bogie position. In the presence of soil of low cohesion, the value of ϕ may change based on the number of wheel turns performed and the presence of the wheel in the rut. The measurements from the images will assist in determining the presence of this effect.

3.1.5 Logging/Trending of Vehicle Performance Data

During vehicle operations, engineering measurements are taken regularly which will help to identify, solar array power generation, stored battery power usage, performance of power converters (regulation), thermal performance of the WTB, external vehicle temperature, rover/lander data transfer performance, motor performance, location estimation and hazard/obstacle detection.

As an example, solar array power output is monitored through three measurements: open cell voltage, shorted circuit cell current and temperature. These cells and a temperature sensor are mounted on the solar panel and sampled during a given sol. An on-board algorithm estimates the power available from the solar panel then compares this power against the appropriate entry in a stored table giving power utilization values for each commanded action (or mode) of rover operation. A command is not executed until adequate power is available from the solar panel to support device loads. The history of command execution and measurements from these sensors provide a record of solar panel performance, which will vary depending on vehicle position and orientation, mission time and environment condition (e.g., see 3.1.10).

3.1.6 Rover Thermal Characterization

The rover has 7 internal and 6 external to the WTB temperature sensors. These sensors will be sampled during,

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both day and night each sol in tracking the thermal characteristics of the vehicle.

The rover WVB has been constructed with a novel insulation material, solid silica aerogel. The operation of the rover during the day results in electronics being powered on. In addition, when the rover is not traversing, available electrical energy from the solar panel is directed to resistive heaters attached to the largest thermal mass in the WVB, the batteries. The resultant heat generated is trapped within the WVB during the day then allowed to soak during the night. During characterization tests, the WVB design has shown less than a 2W thermal leak with the rover capable of developing more than 50W-hr of energy for heating during the day. The monitoring of temperatures internal to the WVB on Mars will verify these results.

The distribution of the external temperature sensors on the rover: one with each camera, one with each front wheel, and one on the solar panel, provide estimates of atmosphere, ground and sky temperatures (respectively). These measurements will supplement those taken at the lander for determining atmospheric structure and meteorology. In addition, they will assist in the WVB performance analysis through measurement of the external environment at the rover.

3.1.7 Rover Imaging Sensor Performance

Engineering telemetry gathered during travel sols are the primary means for the reconstruction of paths taken by the rover across the terrain and evaluation of the navigation and hazard avoidance systems (see 3.1.3). In support of these engineering measurements, the rover and lander cameras will image the tracks produced by the vehicle in the soil after traverses. These images, taken once per sol, can be correlated with the vehicle telemetry and the reconstructed paths to develop and refine the hazard avoidance and navigation algorithms used on the rover.

3.1.8 UHF Link Effectiveness

The rover routinely communicates with the lander, transmitting telemetry and receiving commands. Terrain characteristics, distance, and temperature (of the equipment) can effect these transmissions. The number and types of data transfer errors will be logged and can be correlated with the rover location at the site to develop a model of the UHF link effectiveness.

3.1.9 Material Abrasion

Replacing a band of cleats on one of the middle wheels of the rover is a pattern of strips of materials: a black reference material, aluminum, platinum and nickel. In an experiment this middle wheel is rotated in the soil while the output is sampled from a solar cell located near this wheel and in view of the materials. Reflected light from the materials as measured by the solar cell can be correlated to the amount

of abrasion caused by Martian soil per distance of wheel travel. From experiments conducted on earth a comparison to several known soil types can be made.

3.1.10 Material Adherence

An open solar cell, a shorted solar cell and a temperature sensor located on the solar panel represent the instrumentation used to monitor and estimate the electrical power production of the panel. In addition, a memory rectifier actuated clear cover is mounted over the shorted solar cell and a stack of two quartz crystal monitors are mounted nearby adding to the instrumentation package. At least once per sol, the output from shorted cell is measured with and without the cover. The difference in cell production depends on the amount of dust accumulated on the cover (and thereby the solar panel). The deposited dust is measured by the quartz crystal monitors. The correlation between the amount of dust and cell output measure the effect of dust on solar panel performance during the mission.

3.2 APXS

The APXS and the visible and near infrared filters on the lander imaging system will determine the elemental composition and constrain the mineralogy of rocks and other surface materials at the landing site. The rover places the APXS sensor head on rocks, soil surfaces, in holes dug by the wheels and against rocks that have been abraded by the rover cleats. Close-up images of the sites of APXS sensor placement provided by the rover cameras will enable millimeter resolution of the sampled areas (rock faces, soil). The APXS is planned to be placed against one rock and on one soil surface during the first 7 sols of rover operation. In an extended mission many locations around the landing site will be so sampled. As a final measurement, the rover will place the APXS on a strip of magnetic targets attached to the edge of the rover ramps.

The APXS consists of alpha particle sources and detectors for back scattered alpha particles, protons and x-rays. The APXS determines elemental chemistry of surface materials for most major elements except hydrogen. The approach used is to expose the material to a known radioactive source of alpha energy. The acquisition of returned elastically scattered alpha particles, alpha-proton nuclear reactions and x-rays due to the excitation of the atomic structure of atoms allow identification and determination of the amounts of most chemical elements.

3.3 Lander Assessment

During the mission, the rover cameras will be used to image portions of the lander. The nominal plan is to direct the rover at the landing site to traverse around the lander. Each sol, one of the end-of-traverse images taken by the rover will contain a portion of the lander. At the end of the series of traverses, an image of the lander can be pieced together from the set of images.

4. OPERATION

The operation flow for the rover is driven by a daily command load from earth via the lander. These commands are generated at the rover control station, a silicon graphics workstation which is a part of the MPI ground control operation. At the end of each sol of rover traverse, the camera system on the lander takes a stereo image of the MFX vehicle in the terrain. Those images, portions of a terrain panorama and supporting images from the rover cameras are also displayed at the control station. The operator is able to designate on the displayed image(s) points in the terrain which will serve as goal locations for rover traverses (Wilcox, B. et. al. 1986). The coordinates of these points are transferred into a file containing the commands for execution by the rover on the next sol, in addition, the operator can use a model which, when overlaid on the image of the vehicle, measures the location and heading of the vehicle. This information is also transferred into the command file to be sent to the rover on the next sol to correct any navigation errors. This command file is incorporated into the lander command stream and is sent by the MPI ground control to the lander for transmission to the rover.

Engineering telemetry which is transmitted from the rover to the lander is transmitted back to earth on a priority basis, ensuring that the most critical telemetry is transmitted on the same sol as it is collected. Among such telemetry will be lander images and rover position data needed to develop the next sol's command sequence. All engineering telemetry is placed in the ground data system, a data base that allows access to data by type, time, and other sorting parameters. Analysis of this telemetry is conducted through workstations, accessible to rover engineering personnel.

In this telemetry analysis an engineering go/no-go decision is reached concerning the execution of a nominal "next sol" sequence of rover activities (e.g., see Fig. 2 for the first 7 sols). In the presence of a "go", a brief review of the mission objectives of the next sol of rover operation is performed by members of the experiment teams. Any modification of targets of opportunity (e.g., locations for soil mechanics experiments, rock selected for eventual placement of the APXS) based on a review of the images from the prior sol is evaluated as part of a trafficability and mission time assessment performed by engineering personnel and the rover operator. An agreement on the targets of opportunity results in an update (perhaps) of the sequence of rover activities. This update is used by the rover operator to prepare the command sequence for submission to the rover. A review of the sequence (in a human readable form) by experiment and engineering personnel both for the rover and the MPI mission represents the final check (and edit) before transmission.

5. AUTONOMOUS CONTROL

In order to accomplish the mission objectives, the rover must traverse extended distances within the vicinity of the lander. The once-per-sol commanding strategy of the mission requires that the rover perform these traverses essentially unsupervised by earth-based mission control. The MFX rover uses a strategy of on-board autonomous control which allows the commanding of high-level, goal-oriented commands supported by a hazard avoidance system (Gatlin et. al., 1994; Wilcox, B. et. al. 1988). In this system the rover attempts to determine where to go, drive toward the location, avoid obstacles along the route and decide when (or if) it has made sufficient progress to the goal. In the following sections the key functions which implement this control strategy are briefly discussed.

5.1 Navigation

The rover performs a traverse by executing a "go to waypoint". This command is parameterized by a coordinate, the goal location, referenced to a lander-centered coordinate system. During the traverse, the rover must regularly and autonomously update its position relative to the lander to determine (at a minimum) if it has reached the goal location. This update is accomplished through the processing of a combination of on-board sensor measurements. The vehicle odometer is updated using the encoder reading on the wheel actuators. A single encoder count is registered each time the motor shaft of the actuator completes a revolution. As the wheel motors are driven, the counts accumulated on each of the six wheels are averaged to determine a change in the odometer. This averaged value is used to update the estimated vehicle position in the lander-centered coordinate system.

To change heading the rover executes a command to "turn", which is parameterized with either a heading relative to a reference vector in the lander-centered coordinate system or to an angle relative to the current rover heading. To achieve a new heading, the four outside wheels are cocked to a 'steer-in-place' orientation through driving the steering actuators to the appropriate position as measured by the potentiometers on each actuator. The vehicle is then driven until the commanded orientation is achieved as measured from the rate gyro. This rate gyro is mounted to align its sensitive axis along the nominal vertical axis of the vehicle, allowing such an orientation measurement to be made. Once the commanded orientation is achieved, the integrated angular measurement from the gyro is used to update the vehicle heading reference.

5.2 Traverse Commanding

The "go to waypoint" and "turn" commands are developed by the rover operator using the once each sol stereo image of the rover taken by the lander camera. The operator can select locations on this image (or additional portions of a panorama as available) which referenced in lander-centered coordinates become the goal locations for these commands. These selections are at a sufficient

resolution to (from the perspective of the operator) reach the objective of the traverse and avoid obvious hazards in the process.

5.3 Hazard Avoidance

In achieving the goal locations of its traverse commands, the rover must determine a safe path for traverse at any distance from the lander. The on-board hazard detection system provided by the front camera system and laser light strippers illuminate a part of the region in front of the vehicle. The cameras, with optics tuned to the wavelength of the lasers, image the illuminated terrain. Selected horizontal lines of the image are read and processed. Displacement from a straight line cutting across these horizontal lines indicates the possible presence of an obstacle in the path. The results from each laser and camera image are correlated to develop a sparse map of obstacle distances and heights in front of the vehicle.

The map is then assessed to determine vehicle trafficability: missing scan lines intersections indicate a hole or cliff, height differential above a threshold indicate excessive slope, and excessive height differential of adjacent values in the map indicate a step-type hazard. If a hazard is detected as a result of this assessment, the rover autonomously turns. The hazard detection and assessment is then repeated until a clear path is identified. The rover is then autonomously driven past the hazard. The goal location again becomes the objective of the traverse and the rover turns back to the proper heading.

Another part of the hazard detection function is performed through an assessment of tilt using on-board accelerometers (one aligned to each axis of the vehicle). A tilt measurement beyond a threshold (nominally 30deg) represents a slope hazard. The rover turns away from the hazard, traverses to beyond the hazard, then turns back to the destination.

5.4 Traverse Assessment

Each 'go to waypoint' in a traverse is parameterized with a time value for execution. This time accounts for execution of the path to the commanded position accounting for hazard avoidance activities. The operator selects the amount of time based on an assessment of the terrain. In addition, since an objective of a traverse is for the rover to reach a location for the end-of-sol planning image from the lander camera, the aggregate time is a factor in selecting the time associated with an individual command, the number of commands issued and the mission objective. When a command 'times-out' the rover stops, does not execute further traverse commands in the operative sequence, and sends telemetry. Similarly, if the hazard avoidance system does not detect a clear path within a specified threshold of turns, the rover stops executing further traverse commands.

During the execution of any command and hazard avoidance activity the rover updates position and orientation. An

assessment of progress to the goal location is performed. When the on-board estimates come within a threshold of the goal location, the rover stops, sends telemetry collected during the command execution and proceeds to execute the next command in the operative sequence.

6. CONCLUSION

As of January 1996, the MEX rover has been assembled and delivered to the MPF flight system to begin a program of functional and environmental tests. In addition, the engineering model of the rover will undergo a series of detailed evaluations under a variety of terrain and environmental conditions. During this period, data will be gathered which will establish the characteristics of the vehicle, assist in tuning the parameters controlling autonomous control functions and help in training the engineers who will be operators during the MEX mission.

To achieve its mission objectives, the MEX rover executes a sequence of commands transmitted once per sol from ground control. Given the uncertainty in knowledge of the Martian terrain, the commands are goal oriented requiring the rover to autonomously avoid hazards and determine whether the objective of the command has been achieved. Through the execution of these commands, telemetry is collected which provide the data for the technology experiments. Selected sites are sampled through the APXS sensor. Images are taken of the surrounding terrain and lander to construct a map of the MPF landing site and assess the state of the lander.

7. ACKNOWLEDGMENT

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